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SUBJECT

EFFECTS OF STRAY LIGHT

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NOTES

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Effects of Stray Light

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6 September, 1991

Ann Dinger's analysis of stray light in the SOFIA telescope (see her memo on this topic dated February 1, 1991) has identified a potential problem. The primary and tertiary mirrors are partially illuminated by the bright Earth and partially shaded by the lower edge of the aperture door when the telescope is pointed at a low elevation angle. As the aircraft rolls during flight, the edge of the shadow of the lower edge of the aperture door moves across the mirror, causing a variable background to appear at the focal plane. This will contribute to the noise seen by a focal plane instrument.

This note assesses the practical effect of this background variation taking into account the expected roll rates (derived from Figure ENV-003 of the SOF-1030 Interface Document) and the normal chopping methods used in IR astronomy.

Figure 5 of Ann Dinger's 2/1/91 memo, derived from the Table on page 6 of that memo, shows the background light seen by a detector in the focal plane at a wavelength of 100μ with a 34μ bandpass. These are attached to this memo for reference. I will compare here the magnitude of the background variation with the shot noise from the constant background which is the sum of the telescope emission and the sky emission. Following this, I will scale this ratio with wavelength.

Note that the variation of the background seen in Figure 5 is not exactly what would be seen while observing a given object as the aircraft rolls. Figure 5 shows scattered light as a function of elevation angle with the aircraft flying level. Thus, it is looking at the effect of moving the telescope relative to the fixed Earth plus cavity. The case of interest here is where the cavity moves relative to the fixed Earth plus telescope. This case should be correctly checked, but for now I will assume that the two cases will result in similar effects.

If $P(z)$ is the background power due to scattered Earthlight seen by the detector as a function of zenith angle, z, and $\dot{z}$ is the maximum roll rate of the aircraft, and the instrument is working with a signal chopped at frequency f, then the maximum roll-induced noise, N_r, in one chop cycle is given by

$$N_r = \frac{dP(z)}{dz}\frac{\dot{z}}{2f} \qquad (1a)$$

This is valid if the treatment of the chopped data is to simply subtract a sample in one of the chopped beams from the next sample taken in the other beam.

The more sophisticated approach of subtracting from each data point the *mean* of the two adjacent background points would reduce this noise contribution by a large amount. In this case, the noise depends only on the second derivative of P with z, and is given by:

$$N_r' = \frac{1}{8f^2}\left\{\frac{dP}{dz}\ddot{z} + \frac{d^2P}{dz^2}\dot{z}^2\right\} \tag{1b}$$

We now compare the results provided by equations (1a) and (1b) with the shot noise on the constant background from the telescope and sky, N_s, given by

$$N_s = \left(\frac{P_B hc}{f\lambda}\right)^{\frac{1}{2}} \tag{2}$$

where P_B is the background power. Here the integration time is taken to be a full chop cycle because we are subtracting a half-cycle integration on the background from a half-cycle integration on the object plus background.

In the worst case at 100μ, dP/dz is 1.5×10^{-14} W/degree, d^2P/dz^2 is 3.3×10^{-15} W/deg^2, $\dot{z}$ is 1.8 degree/sec, $\ddot{z}$ is 4.1 degrees/sec^2 and f is 10 Hz. The noise, N_r, is then 1.4×10^{-15} W while N'_r is 9×10^{-17} W, a factor of 15 lower than N_r. The constant background, P_B , is 3.4×10^{-10} W. Thus, the ratio $R = N_r/N_s$ is 5.2 and $R' = N'_r/N_s$ is 0.4. In a complete integration lasting many roll cycles, the variation in the average value of the roll-induced background noise will decrease linearly with the integration time since this is a nearly periodic, rather than random, process. The average value of the shot noise will decrease with the square root of the integration time, so for sufficiently long integration times, the roll-induced noise will become smaller than the shot noise on the background.

Next, let us attempt to scale this result to other wavelengths in an approximate way. First, to make the worst case as a function of wavelength, we must assume that the atmosphere is clear so that the (warm) surface is the source of illumination rather than the (cold) tropopause, as was assumed above. This is true at all the wavelengths in the table below except for 50 and 100 microns. Then we must scale R and R' to account for the different wavelength dependence of the Earth emission and the telescope emission. Here we assume that the telescope emission is substantially larger than sky emission. The scaled ratio R is given by

$$R(\lambda) = R(100)\ \frac{B_\lambda(T_E)}{B_{100}(T_{Tr})}\left(\frac{B_\lambda(T_T)}{B_{100}(T_T)}\right)^{-\frac{1}{2}} \tag{3}$$

where $B_\lambda(T)$ is the Planck function per unit wavelength interval. R' is scaled in the same way. T_E is the temperature of the Earth (280K), T_{Tr} is the tropopause temperature (220K) and T_T is the telescope temperature (240K). All emissivities are assumed to be wavelength-independent. The scaled ratios are given in the table below. Note that the 100μ value is higher than that given earlier because of the assumption implicit in this table that the atmosphere is clear.

Wavelength (μ)	$R(\lambda)$	$R'(\lambda)$
3	27	1.8
5	130	8.7
10	200	13
20	107	7.1
50	25	1.7
100	7.1	0.5

Thus, the problem of the variable background is most severe at wavelengths near the peak of the Earth's blackbody emission.

At first glance, the problem appears to be serious through most of the near and mid infrared spectral region. However, several factors combine to reduce the seriousness of the problem. First, the estimate above is a worst case estimate, assuming that the first and second derivatives of $P(z)$, $\dot{z}$ and $\ddot{z}$ are all simultaneously at their maximum values. Second, long integrations will be less sensitive to the roll-induced noise, as explained above. Third, a higher-order background interpolation scheme could be used to further reduce the effect of the background variation. Fourth, it would be possible to correlate the background variation with the aircraft roll orientation as recorded by the housekeeping system, and then use the recorded roll data to reduce the impact of the background variation on the data. Fifth, this problem only occurs at elevation angles below 30°. Finally, observations at the shorter wavelengths will be done with array detectors in the future. In this case, the background can be obtained as part of the image and the time-dependent background is entirely eliminated. Thus, we do not anticipate having a serious problem at the shorter wavelengths either.